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Alkali Metal Rankine Cycle Boiler Technology Challenges and Some Potential Solutions for Space Nuclear Power and Propulsion Applications

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ALKALI METAL RANKINE CYCLE BOILER TECHNOLOGY CHALLENGES AND SOME POTENTIAL SOLUTIONS FOR SPACE NUCLEAR POWER AND PROPULSION APPLICATIONS

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SUMMARY

Alkali metal boilers are of interest for application to future space Rankine cycle power conversion systems. Significant progress on such boilers was accomplished in the 1960's and early 1970's, but development was not continued to operational systems since NASA's plans for future space missions were drastically curtailed in the early 1970's. In particular, piloted Mars missions were indefinitely deferred. With the announcement of the Space Exploration Initiative (SEI) in July 1989 by President Bush, interest was rekindled in challenging space missions and, consequently in space nuclear power and propulsion. Nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) were proposed for interplanetary space vehicles, particularly for Mars missions. The potassium Rankine power conversion cycle became of interest to provide electric power for NEP vehicles and for "dual-mode" NTP vehicles, where the same reactor could be used directly for propulsion and (with an additional coolant loop) for power. Although the boiler is not a major contributor to system mass, it is of critical importance because of its interaction with the rest of the power conversion system; it can cause problems for other components such as excess liquid droplets entering the turbine, thereby reducing its life, or more critically, it can drive instabilities—some severe enough to cause system failure.

Funding for the SEI and its associated technology program from 1990 to 1993 was not sufficient to support significant new work on Rankine cycle boilers for space applications. In Fiscal Year 1994, funding for these challenging missions and technologies has again been curtailed, and planning for the future is very uncertain. The purpose of this paper is to review the technologies developed in the 1960's and 1970's in the light of the recent SEI applications. In this way, future Rankine cycle boiler programs may be conducted most efficiently. This report is aimed at evaluating alkali metal boiler technology for space Rankine cycle systems. Research is summarized on the problems of flow stability, liquid carryover, pressure drop and heat transfer, and on potential solutions developed, primarily those developed by the NASA Lewis Research Center in the 1960's and early 1970's.

INTRODUCTION

Alkali metal boilers are of interest for future space Rankine cycle power conversion systems. Significant progress was made in the 1960's and early 1970's on boiler technology, but flight hardware was not developed since NASA's plans were curtailed in the early 1970's. In particular piloted missions to Mars were indefinitely deferred until President Bush announced the Space Exploration Initiative (SEI) in July 1989. Nuclear electric propulsion (NEP) (e.g., refs. 1 and 2) and nuclear thermal propulsion (NTP) (e.g., ref. 3) have been proposed for both piloted and cargo vehicles, particularly for Mars missions. The potassium Rankine cycle is of interest to provide electric power for NEP vehicles (e.g., refs. 4 to 8) and for "dual-mode" NTP vehicles, where the same reactor is used directly for propulsion and (with an

additional power conversion loop) for electric power generation (e.g., refs. 9 to 10). Science missions to the outer planets (e.g., ref. 11) and cargo transfer from low-Earth orbit (LEO) to geosynchronous orbit (GEO) or low-lunar orbit (LLO) (e.g., ref. 12) could also benefit from NEP, but are generally at lower power levels where other conversion systems offer advantages over the Rankine cycle.

For higher power levels Rankine cycle systems are very attractive in system trade studies (e.g., refs. 4, 13, and 14). In a Rankine cycle system, power is generated by turboalternators driven by vapor generated in the boiler. The vapor is then condensed and the cycle waste heat is rejected in a radiator. In order to minimize the mass of the radiator (the largest component of the power conversion system) and to achieve high efficiency, boiling temperatures on the order of 1450 K are desired. Alkali metals (such as sodium or potassium) may be considered as the working fluid in order to meet the high-temperature requirements. In turn suitable refractory containment materials for the alkali metals will be required, such as niobium or tantalum, for system components. In addition to the high-temperature requirements, the power system must operate reliably for periods of 10 000 hr or more.

For spacecraft power systems, the Rankine cycle with a once-through boiler is highly attractive. Although the boiler has a relatively low mass, it is critically important because of its interaction with the rest of the power conversion system; it can cause problems for other components such as excess liquid droplets entering the turbine, reducing its life, or more critically, it can drive fluid instabilities—some severe enough to cause system failure (e.g., refs. 6 and 15).

Limited technology development funding for the SEI precluded a renewed effort on Rankine cycle boilers for space application. In Fiscal Year 1994 funding for these challenging missions and technologies has again been curtailed, and planning for the future is very uncertain. This paper reviews the technologies developed in the 1960's and 1970's with an eye toward SEI applications. In this way, future Rankine cycle boiler programs can be conducted most efficiently. This report is aimed at evaluating alkali metal boiler technology applicable to space Rankine cycle systems. The report focuses primarily on work performed at the NASA Lewis Research Center and, to a lesser extent, its contractors in the time period between 1961 and 1971 (ref. 15). The emphasis of that research was to develop the technologies for once-through, compact boilers with high-heat fluxes, to generate dry vapor stably, without gravity for phase separation. Many different experimental approaches to the problem were pursued, and several potential solutions were developed. Reference 15 includes many pertinent references and a bibliography dating back to 1937. Additional summary information may be found in references 16 and 17.

REVIEW OF EARLIER WORK

Many of the experiments to be discussed were conducted with water, since experimentation with the alkali metals is both difficult and expensive to perform. Furthermore, with the exception of liquid thermal conductivity, low-pressure water has boiling properties similar to those of alkali metals.

Holcomb (ref. 7) reviewed some of the pertinent past Rankine cycle research and development activities. In the SNAP-50/SPUR program, Pratt & Whitney Aircraft designed a system in 1961 featuring a 2.2 MW_t lithium-cooled fast reactor with a 0.3 MW_e potassium Rankine cycle power conversion system. The General Electric Company (GE) focused on component development for the boiler, turbine, and condenser. Oak Ridge National Laboratory (ORNL) designed a system in 1959 featuring a 1 MW_t direct-boiling potassium cooled fast reactor with a 0.15-MW_e potassium Rankine cycle power conversion system. ORNL also focused on component development for the reactor, turbine-pump, and condenser.

Boiling Characteristics

Background.—During the boiling of a fluid flowing through a channel, several heat transfer regimes are encountered. A typical case is illustrated in figure 1. The liquid to be vaporized enters the channel and is heated in the liquid phase to the point where bubble nucleation first occurs. Nucleate boiling continues until enough vapor is generated that the resulting increase in velocity is sufficient to suppress nucleation (by increasing the heat transfer coefficient, thus lowering the wall temperature). Beyond this point, heat is transferred to the thin liquid film and vaporization occurs at the liquid-vapor interface. Throughout these boiling regimes, liquid is being entrained into the vapor core. In spite of any redeposition of liquid from the core to the film, at some point there is no longer sufficient liquid to wet the wall and the liquid film breaks down, with a large reduction in heat transfer coefficient, often more than an order of magnitude. This transition has been variously termed “boiling crisis,” “departure from nucleate boiling,” “onset of dry-wall boiling,” and “burnout,” as well as other names. This film breakdown is generally followed by a transitional regime wherein a considerable amount of liquid remains on the wall, although no longer a continuous film. Eventually only a few droplets remain on the wall, and most of the heat added through the wall goes into heating the vapor. It then becomes very difficult to vaporize the remaining droplets. (Note that the “boiling crisis” is not really a crisis in a heat exchanger boiler; however, it could present severe problems in such applications as a direct-boiling reactor.)

In order to design a forced-flow boiler, it is necessary to be able to predict the heat transfer and pressure drop characteristics in each of these regimes. This problem is complicated by the wide variety of possible two-phase flow regimes and by thermodynamic nonequilibria, such as subcooled boiling in many fluids, liquid superheat in alkali metals, and liquid droplets entrained in superheated vapor. It is also very important that the boiler not interact with other system components to produce instabilities. The following sections describe these problems in more detail.

Stability and dynamics problems.—The problem of boiler instabilities is quite serious in systems using forced-flow, once-through boilers. Such instabilities lead to poor performance of the system and can lead to failure. Lowdermilk, Lanzo, and Siegel (ref. 18) found that flow oscillations could cause a large decrease in the heat flux at the boiling crisis. The instability could be prevented by restricting the flow upstream of the boiler, thereby decoupling the upstream liquid leg (which may also contain vapor or gas voids). In this regard, they found that a compressible volume upstream of the boiler had a destabilizing effect. It has been reported by others that restricting the boiler exit has a destabilizing effect. Thus, the boiler feed system, inlet, and exit geometries are all quite important.

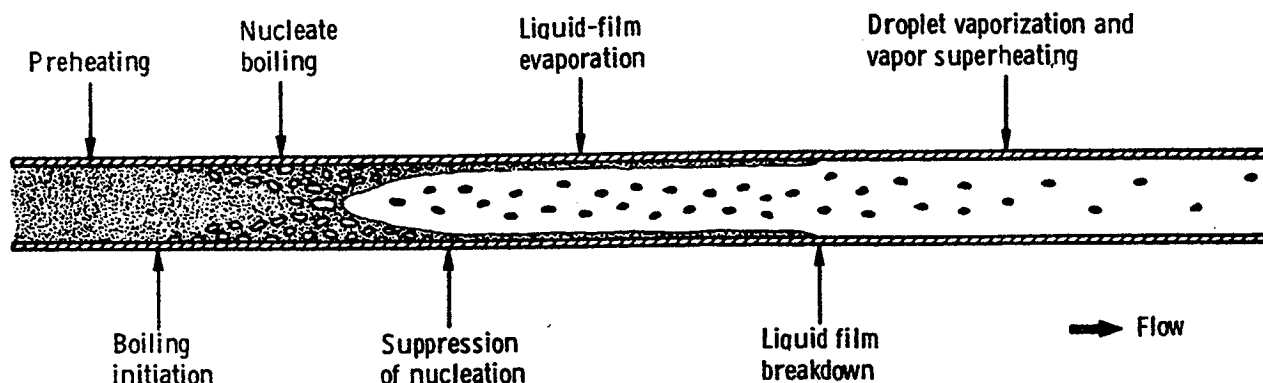


Figure 1.—Typical heat-transfer regimes for boiling in a flow channel.

The first type of instability to receive much attention with regard to forced-flow boilers was the flow excursion instability, sometimes called the "Ledinegg instability." This problem generally results from improper matching of pump and boiler hydraulic characteristics, as was first reported by Ledinegg (ref. 19). This type of instability may be explained with the aid of a typical curve of pressure drop ΔP against boiling fluid flow rate W_b at constant heat input, as shown in figure 2 (from ref. 20). If the operating point is in the negative-slope portion of the boiler pressure-drop curve when the slope of the supply system curve is less steep than the slope of the boiler curve, the system is unstable. The operating point may jump to one of the other two points of intersection. This type of instability may be avoided by increasing the slope of the supply system curve, that is, by increasing the system pressure drop to steepen the pump characteristic (e.g., ref. 20).

As research and development of Rankine-cycle power systems continued, other modes of instability were recognized, such as boiler/feed system coupling, excursions caused by flashing of superheated liquid (in alkali metals), and interactions of boiler and condenser. Boiler/feed system coupling instabilities occur when the dynamic or time-varying flow resistances of the boiler and its feed system produce, instantaneously, a situation similar to the Ledinegg instability described in the preceding paragraph. However, since this instability is caused by dynamic flow resistances or more generally impedances (by analogy to electric circuits), it produces oscillations rather than excursions (e.g., ref. 21).

The instabilities due to both actions in the condenser and breakdown of liquid superheat are related to the sudden formation or collapse of vapor. The rapid collapse of a vapor void may cause reverse flow downstream of the void and simultaneously increase the flow rate upstream. This obviously will cause instabilities throughout the system. With sudden void formation, such as in flashing of superheated liquid, the reverse (or at least reduced) flow occurs upstream of the void and increasing flow occurs downstream, but the destabilizing effects are similar.

Initiation of vaporization.—In order to initiate vaporization in a liquid, either the pressure must be lowered below the saturation pressure, or the temperature must be raised above saturation temperature.

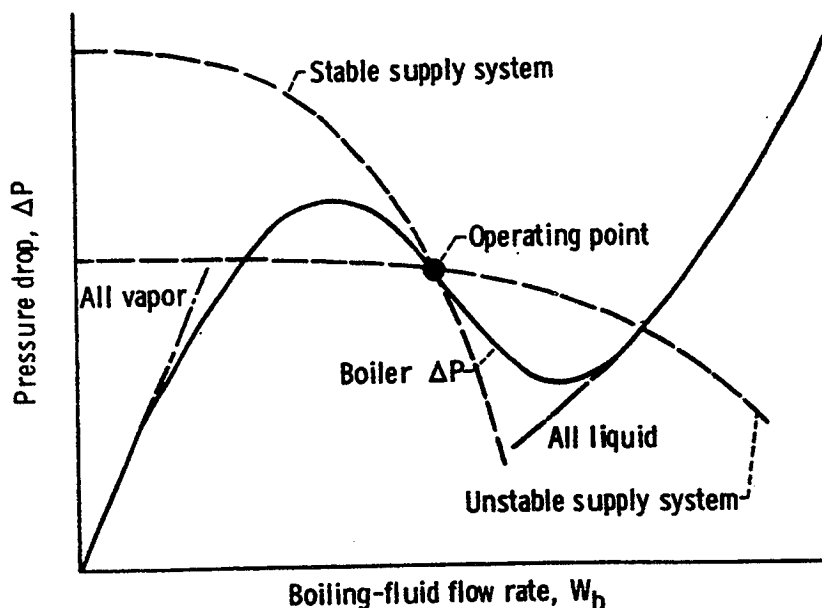


Figure 2.—Pressure drop as function of flow rate for typical boiler and supply system at constant heat input (ref. 20).

Vaporization generally cannot be initiated exactly at saturation because of surface tension effects and the unavailability of nucleating sites. For a spherical bubble of radius r at saturation pressure P_s to grow, the pressure P_ℓ of the surrounding liquid must be less than

$$P_\ell = P_s - 2\sigma/r$$

where σ is the surface tension. This equation is derived from a force balance on a static, spherical bubble. The nonequilibrium condition required to initiate vaporization can be achieved by different processes; therefore, there are several different ways the nonequilibrium can be defined. Terms such as "liquid tension" (ref. 22), "bulk superheat," and "wall superheat" are used.

In boiling initiation studies the superheat terminology is generally used. For nonmetallic liquids the term "wall superheat" is commonly used, since boiling can usually be caused by bringing the liquid in contact with a sufficiently hot surface, even when the bulk temperature of the liquid is less than saturation. Surface boiling with the liquid bulk temperature less than saturation is termed "subcooled boiling." The important parameters in determining the wall superheat are heat flux, mass velocity, degree of liquid bulk subcooling, fluid physical properties, and surface condition.

In order to boil the metallic fluids, it is often necessary to raise the liquid bulk temperature considerably above saturation (e.g., refs. 23 and 24); thus, the term "bulk superheat" $T_\ell - T_s$ is used. The effects of physical properties and surface conditions have been investigated (e.g., refs. 23 to 26); Chen (ref. 25); and Holtz (ref. 26) have pointed out the importance of the pressure-temperature history of the fluid and surface. The effects of mass velocity and temperature had not been resolved in the early 1970's.

When vaporization is achieved by lowering the pressure of the liquid below saturation, the term "liquid tension" is generally used to describe the nonequilibrium condition before vaporization occurs. The liquid tension is given by $P_s - P_\ell$. Such terminology has commonly been used in cavitation studies (e.g., ref. 27). The existence of liquids at pressures below zero absolute ("absolute tension") has long been known (ref. 22). This phenomenon has been attributed to the considerable magnitude of the intermolecular cohesive forces (ref. 28). Many experimental measurements of these negative absolute pressures appear in the literature, such as references 29 and 30 for water and reference 31 for organic liquids.

Flow patterns.—A multitude of flow patterns is conceivable for two phases flowing concurrently, as is the case for a boiler channel. This makes it difficult to develop reliable predictions of two-phase pressure drop, heat transfer coefficient, and boiling crisis. Some of the flow patterns typically encountered are shown in figure 3. These are only a few of the possibilities; other flow patterns are plug, wave, dispersed, fog, spray-annular, froth, and rivulet. Most flow pattern studies have been with adiabatic, two-component systems, although some data exist for diabatic conditions. These results are usually presented in flow pattern maps similar to that of Baker (ref. 32), which is shown in figure 4 (definitions of these complicated dimensionless parameters may be found in ref. 15 or 32).

Pressure drop.—Knowledge of boiling pressure drop is important in the design of power conversion systems. The pressure drop must be known to determine local saturation temperatures and pumping power requirements. The boiling pressure drop (both time-averaged and instantaneous) is also important in system dynamics.

Helical-flow-promoting inserts are often used in forced-flow boilers to improve separation of the phases, to increase heat transfer coefficients (thereby reducing the required heat transfer area), and to produce a more stable and reliable system. However, these benefits are accompanied by a larger pressure drop across the boiler. Thus, in order to achieve an optimal design, it is necessary to know the pressure

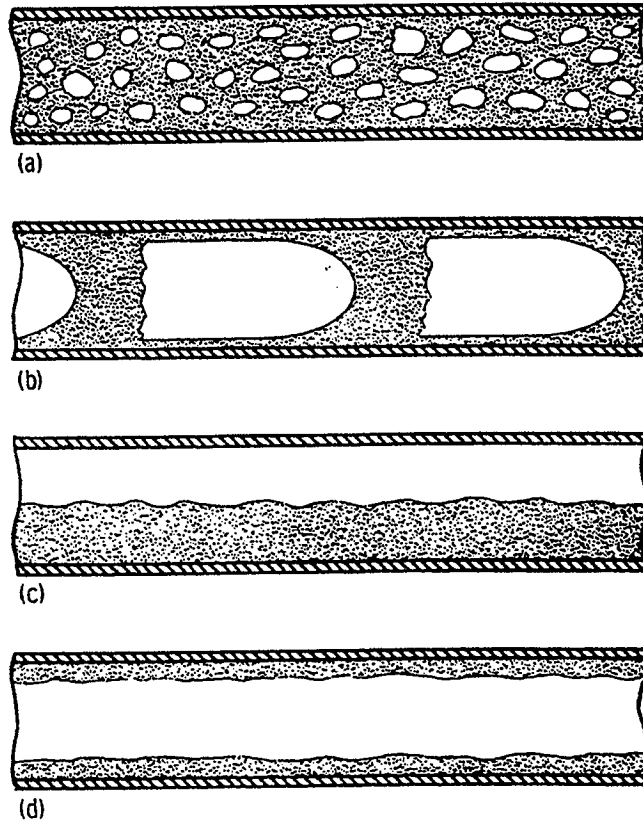


Figure 3.—Typical two-phase flow patterns. (a) Bubbly flow. (b) Slug flow. (c) Stratified flow. (d) Annular flow.

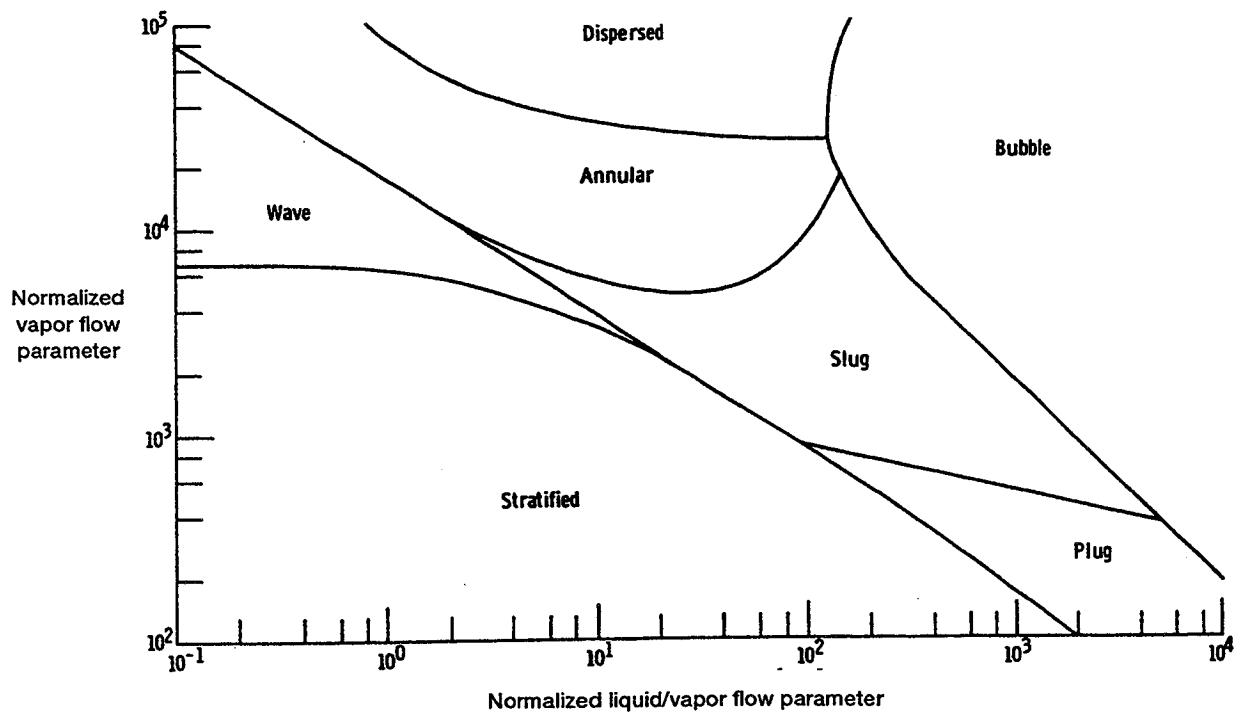


Figure 4.—Flow pattern map of Baker (ref. 32); horizontal flow.

drop penalties imposed by the helical flow inserts as well as the performance improvements obtained by their use. Prediction methods for pressure drop are discussed in reference 15.

Heat transfer.—Although there have been numerous studies of boiling heat transfer, there was still no generally applicable prediction available in the early 1970's, particularly for high-density-ratio fluids such as alkali metals and low-pressure water. This is especially true of the subcooled boiling regime, where nonequilibrium effects are important, although subcooled boiling heat transfer correlations give reasonable design approximations in many cases. Some correlations proposed for subcooled and net-quality boiling are discussed in reference 15.

Typical variations of the boiling heat transfer coefficient and quality with axial distance through a boiling heat exchanger are shown in figure 5. The heat transfer coefficient h is normalized to the all-liquid value h_l ; quality x is the vapor mass fraction, and axial distance z is normalized to the heated length of the boiler L_H . Boiling heat transfer coefficients are much higher than all-liquid values prior to boiling crisis and then decrease rapidly with distance, eventually reaching a value on the order of a gas heat transfer coefficient. For purposes of discussion, three heat transfer regimes are defined: the subcooled regime, from the inception of boiling to zero heat-balance quality; net-quality boiling prior to the crisis; and the post-crisis regime. This is of course, a great oversimplification.

Drying of vapor.—In conventional stationary powerplants, generally no attempt is made to vaporize all the incoming liquid; instead the vapor and liquid are separated, and the remaining liquid is recirculated. However, compact systems, such as those for space use, are usually designed to vaporize all the liquid, using the "once-through" approach. In order to dry the vapor, the two-phase mixture is often swirled within the boiler, thus centrifuging the liquid to the wall, where it can be vaporized.

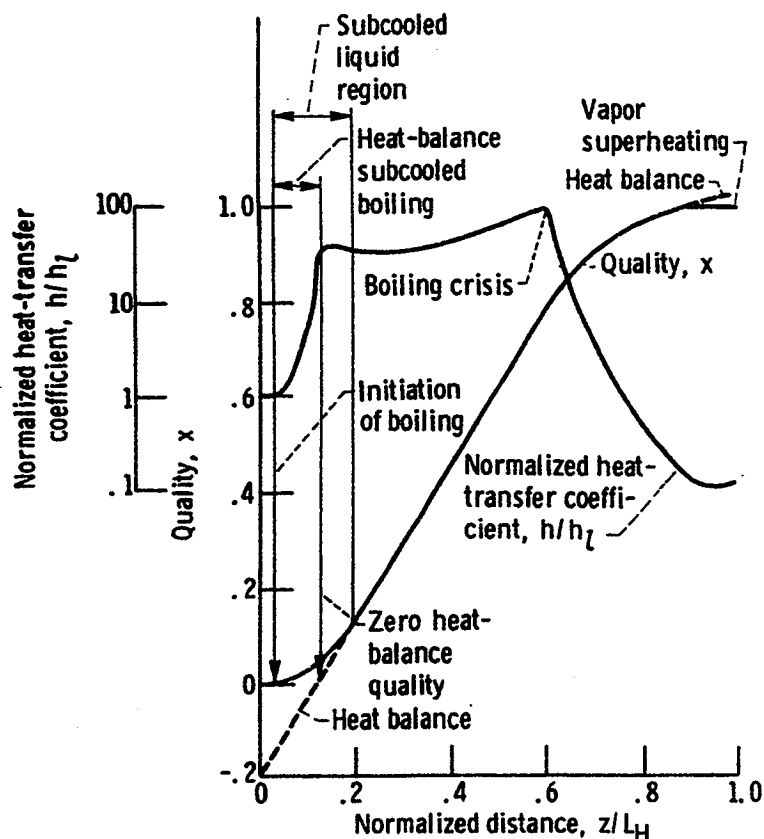


Figure 5.—Typical boiling heat transfer performance.

This swirl has often been obtained by tube inserts and/or tube coiling. More innovative approaches investigated include the rotating boiler and the cyclone boiler. Also, a separation device may be feasible, such as the rotary fluid management device suggested by Mills (ref. 6). Still another method is the cross flow heat exchanger, wherein the two-phase flow passes through a bank of heated tubes on which the liquid impinges and is vaporized (ref. 33).

Boiler Configurations

A number of configurations designed and tested in the 1960's and 1970's are reviewed in reference 15. As pointed out by Holcomb (ref. 7), there exists a significant technology base for Rankine cycle components for 0.1 to 0.3 MW_e systems. Mills (ref. 6) states that over 20 000 hr of tests were performed from 1960 to 1972. Much of that work was on single tube boilers, representing one of the many tubes which would be required for these power levels, and with water to simulate the alkali metals. Typically these tests should be considered subscale component tests in the context of the applications most recently of interest. For power generation on an NTP vehicle, system power levels of 0.025 to 0.050 MW_e may be required (refs. 9 and 10). The NEP studies of the early 1990's indicate that the power levels required for a Rankine cycle system range from 1.5 MW_e (ref. 2) to 40 MW_e (ref. 34). Based on SP-100 reactor technology for a 5-MW_e system, the thermal power required would be 19 to 48 MW_t (ref. 5).

Plain, straight tubes with no inserts.—This is the simplest forced-flow, once-through boiler design. Many experiments are reviewed in reference 15 for such boilers, both heat exchangers and electrically heated tubes. Experiments were conducted at NASA Lewis on sodium boiling in a refractory-metal, single-tube-in-shell heat exchanger boiler (ref. 35). Average overall heat transfer coefficients, two-phase pressure drops and boiling crisis conditions were obtained. Both steady and unsteady boiling performances were evaluated. The boiler heat transfer performance depended greatly on boiler inlet flow condition, whether liquid or two-phase. Critical (boiling crisis) qualities in excess of 0.90 were sometimes obtained under steady conditions. But also, liquid bulk superheats as high as 140 K were obtained in the boiler before the initiation of boiling.

The initiation of boiling was one of the major problems encountered because the alkali metals have the ability to remain in the liquid state at bulk temperatures well above saturation. However, with two-phase flow at the boiler inlet the problem of liquid superheat was eliminated. The effect on boiler performance of flashing at the upstream orifice was quite complicated since a liquid boiler-inlet condition gave both the most steady and the most unsteady results of the entire investigation. Figure 6 illustrates the differences between two-phase and liquid inlet conditions. Shell and boiling-fluid temperatures are plotted against axial distance from the tube inlet. Both sets of conditions were essentially the same except that in one case, the sodium entering the boiler was in a two-phase state (flashing at the upstream orifice) and, in the other case, the inlet feed was a subcooled liquid. For the two-phase feed the shell temperature increased along the boiler, following a generally smooth curve, which indicates a continuous increase in vapor quality and the same general regime of heat transfer. (The boiling-fluid temperature was estimated from pressure drop considerations, as no local fluid temperature measurements were made.

In contrast, the shell temperatures for the liquid inlet case showed a slight initial increase and then were uniform to about halfway along the boiler. At this point there was a sudden transition and the shell temperatures increased rapidly and followed a curve very similar to that for the two-phase inlet condition. The isothermal zone represented a region of liquid sodium superheated by about 60 K. Sudden flashing from this superheat would yield a heat-balance vapor quality of about 0.02. Beyond this point, the overall heat-transfer coefficient was even greater than that for the two-phase inlet case. The reduced exit quality, in this case for the liquid inlet condition, reflected the sizeable length of the boiler over which little or no

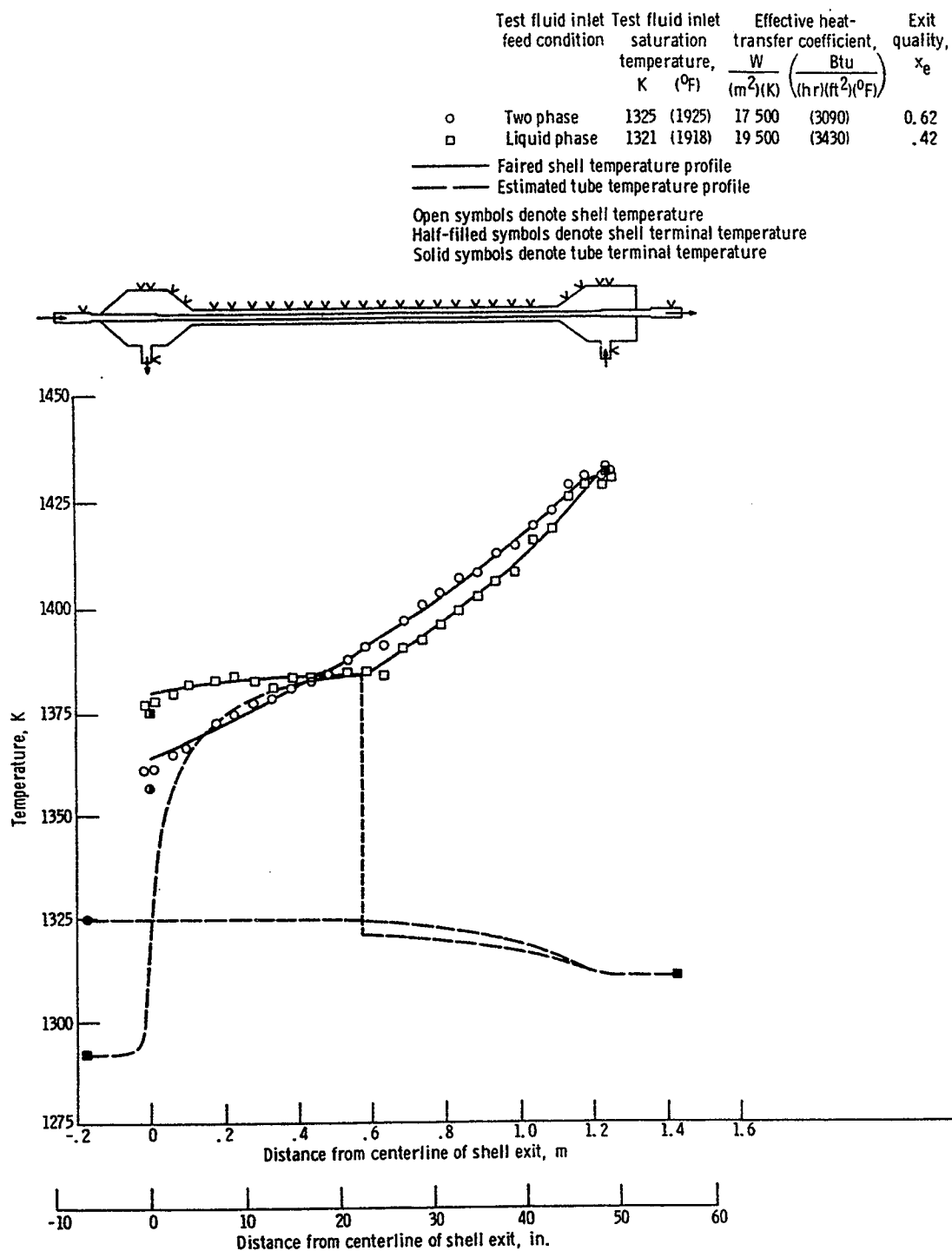


Figure 6.—Comparison of sodium boiler temperature profiles for two-phase and liquid boiling-fluid inlet conditions. Nominal boiling fluid flow rate, 27 g/sec; nominal heating fluid flow rate, 630 g/sec.

heat transfer took place. Obviously, these flow regimes were not optimum, and they could not be conveniently studied or visualized in such a complex, high-temperature facility.

To explore these phenomena further, a series of experiments on water-boiling heat exchangers was conducted at NASA Lewis. Results of these tests as well as for electrically-heated tubes are discussed in reference 15. Since complete vaporization to a vapor quality of 1.0 was not obtained for any case tested

with plain straight tubes without inserts, these results were primarily useful in establishing criteria for the selection of necessary inserts and inlet devices. Inlet pressure drop devices and inserts were required to achieve the desired performance, as discussed in the following sections.

Tube inserts and/or coiling.—Swirl-generating inserts, tube coiling, or a combination of both have commonly been used to improve boiler tube performance. Inlet-region plugs also help to prevent the formation of the generally unstable slug-flow regime. Several types of helical flow inserts have been tested in alkali metal boilers (refs. 36 and 37). The purpose of such inserts is to maintain liquid on the boiler tube wall at high vapor qualities. For many of the experiments a full-length helical wire insert was used for this purpose. Typical inserts are shown in figure 7. Experiments with heat-exchanger boilers with inserts and/or coiling are summarized in reference 15. These approaches have resulted in varying degrees of improvement, as for example in the SNAP-8 mercury boiler development program (e.g., ref. 38). Generally, these swirl techniques improve overall performance. But, they increase pressure drop and tend to promote rivulet flow with its associated problems, such as vapor superheat with liquid still present (e.g., refs. 38 and 39). Part of the problem may have been due to the shear of high-velocity vapor on the liquid, causing the liquid film to be torn apart.

From the results of these tests reviewed in reference 15, it is apparent that inserts can improve boiler performance. Swirl devices delay the boiling crisis to higher qualities at the expense of increased pressure drop. Inlet-region plugs contribute to flow stability by reducing the tendency for reverse flow and slug flow, with minimal increase in pressure drop. However, stable and complete vaporization was not consistently obtained with these devices alone.

Inlet restrictors.—Some of the boiling flow instabilities described in the previous sections were attributed to insufficient boiler-inlet pressure drop. As a consequence, various inlet restrictors were studied. The following paragraphs describe tests with water and with potassium performed on boilers with inserts and inlet restrictors (ref. 15).

Water boilers: Since at exit quality of 1.0 could not be obtained with orifices at the inlet of water boilers, at least over the range of conditions tested, and since the orifice used with the sodium boiler was not completely satisfactory, alternative devices were tested to provide the pressure drop required. Instead of orifices, venturis were used in subsequent water-boiling tests. With a venturi, much more of the inlet-to-minimum pressure difference can be recovered than for an orifice, reducing losses, and the flow is much more uniformly distributed to the wall at the start of heating. Furthermore, as discussed in detail in reference 15, cavitation or flashing can be induced in the very low throat pressure venturi, leading to two-phase choking, which effectively isolates the feed system from any disturbances generated in the boiler.

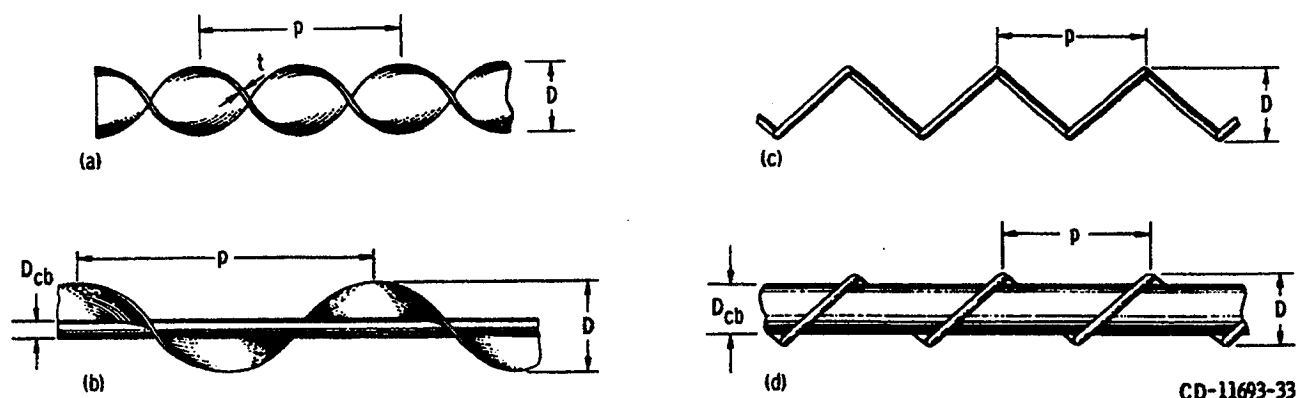


Figure 7.—Types of boiler tube inserts. (a) Twisted-tape insert. (b) Helical vane insert. (c) Helical wire insert. (d) Helical wire insert with plug.

Plots of exit quality and boiler pressure drop against boiler exit temperature difference (heating fluid minus boiling fluid) for the 0.78-mm throat diameter venturi inlet, inlet-region plug, and helical-wire insert are shown in figures 8(a) and (b), respectively, for a boiling-fluid flow rate of about 10 g/sec at otherwise nominal conditions. (Stable operation could not be obtained at 7.5 g/sec, probably because of insufficient pressure drop and/or unsteady cavitation of the venturi.) Vapor superheat was first indicated

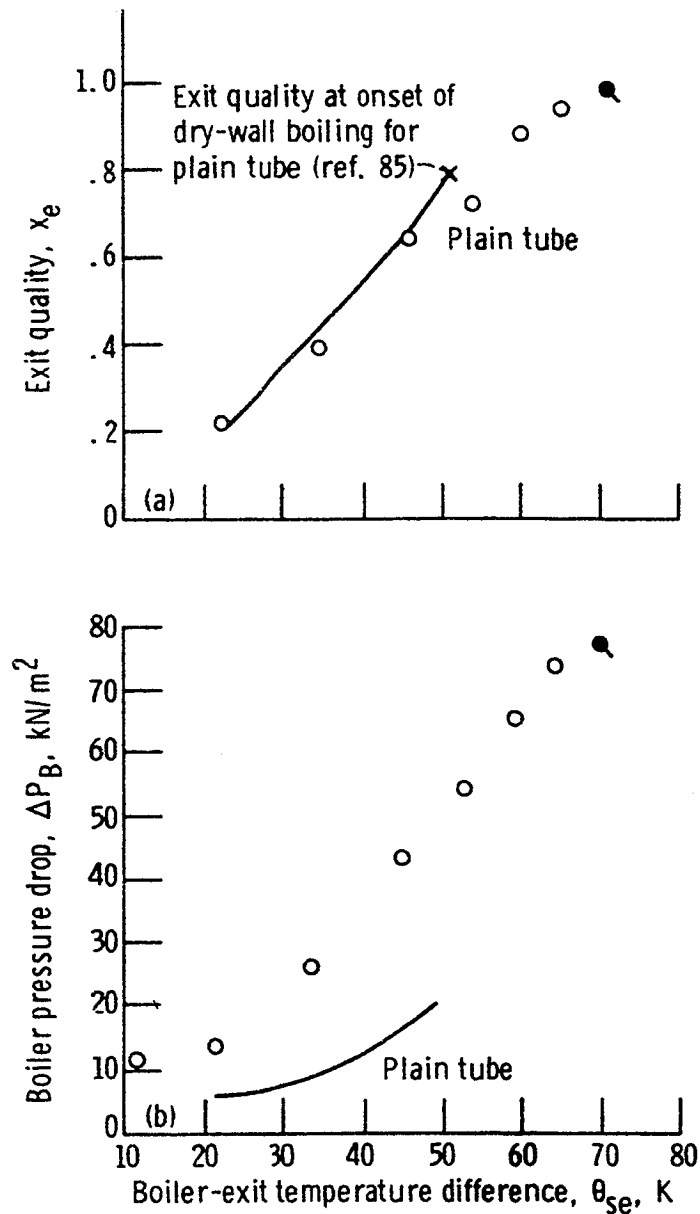


Figure 8.—Boiler performance as function of boiler-exit temperature difference with helical wire insert, 0.78-mm-throat-diameter venturi, and 25.4-cm plug. Heating-fluid flow rate, ~1.0 kg/sec boiling-fluid flow rate, ~10 g/sec; inlet temperature, ~300 K; exit pressure, ~117 kN/m²abs.

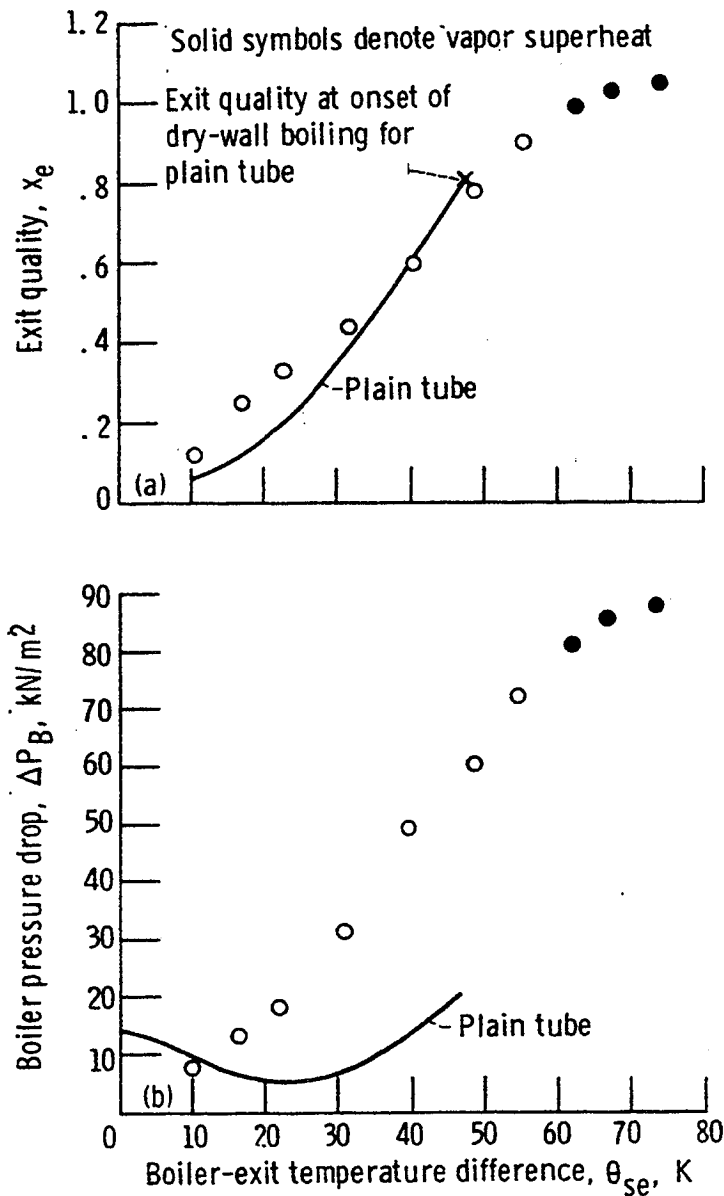


Figure 9.—Boiler performance as function of boiler-exit temperature difference with helical wire insert, 0.78-mm-throat-diameter venturi, and 25.4-cm plug. Heating-fluid flow rate, ~ 1.0 kg/sec; boiling-fluid flow rate, ~ 10 g/sec; inlet temperature, 372 to 389 K; exit pressure, ~ 117 kN/m² abs.

at exit vapor quality $x_e = 0.98$; flow oscillations in the range of ± 5 to ± 10 percent were observed at that point. No erratic boiling-fluid inlet temperature behavior like that seen without an inlet device was observed. The pressure drop across the venturi and its diffuser was about 170 kN/m² with a flow rate of 10 g/sec and an inlet temperature of 300 K.

Another series of runs was made with the same flow rates and boiler exit pressure but with higher boiling-fluid inlet temperature (371 to 389 K). The exit quality and boiler pressure drop are again plotted against the boiler exit temperature difference for this series in figures 9(a) and (b), respectively. Vapor superheat was observed at exit qualities from 0.96 to 1.02. Boiling-fluid flow oscillations were less than ± 5 percent; however, additional pressure drop (as much as 70 kN/m²) was required at the upstream throttle valve in addition to the venturi pressure drop for flow stability at the high exit qualities. In these

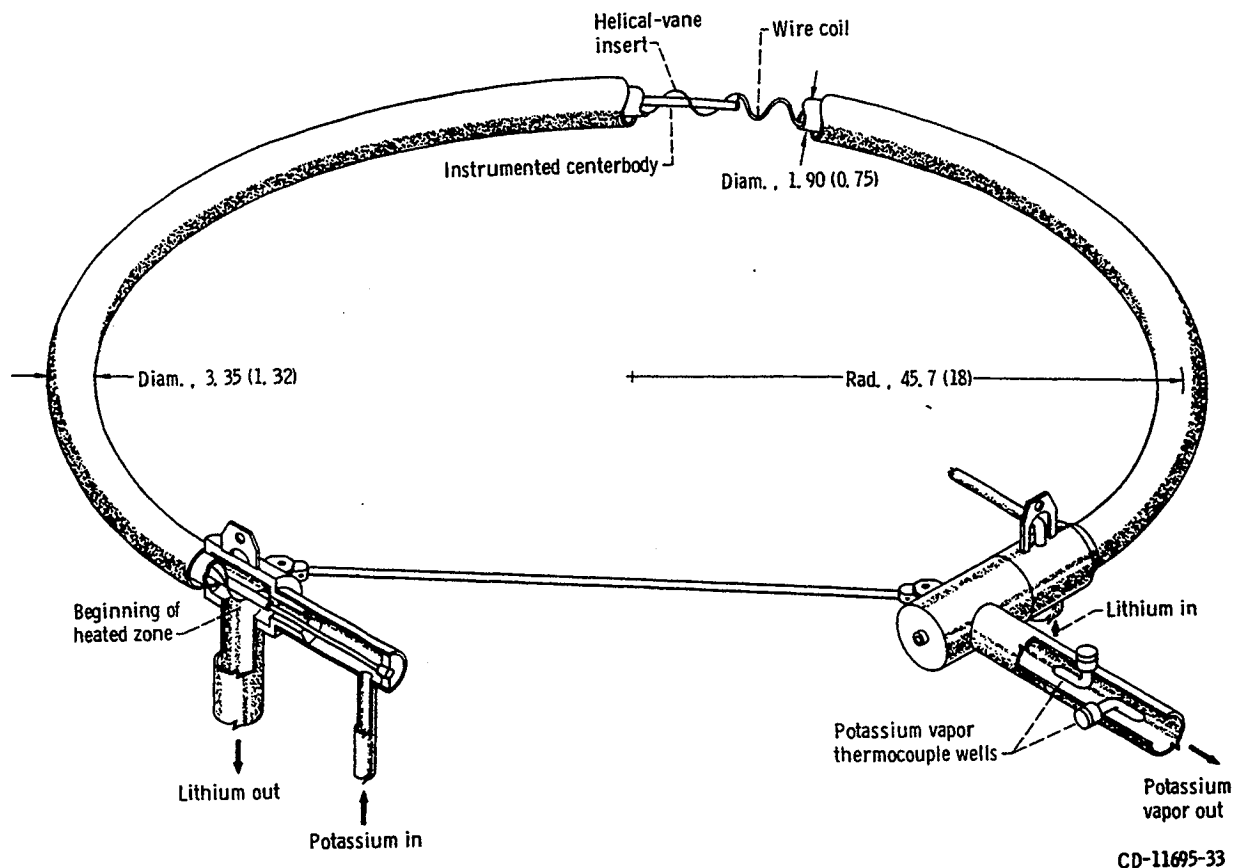


Figure 10.—Schematic of single-tube potassium boiler. (Dimensions are in cm.)

runs, conditions were established such that flashing (sudden vaporization) probably occurred in the venturi, but persistence of the vapor into the boiler tube was marginal.

Potassium boiler: The General Electric advanced Rankine cycle test facility used for these tests is described in references 40 to 42. The lithium-heated boiler tube arrangement is shown in figure 10. Two T-111 alloy boiler tubes were tested, differing primarily in that the second included an inlet venturi. The first boiler (without venturi) had a composite insert consisting of a center plug wrapped with a single-pitch ribbon-type helical vane. Following this the plug tapered down to a 0.64-cm-diameter centerbody (hollow for thermocouple installations) that extended for about two-thirds of the boiler length as did the helical vane. Then the helical vane joined (at the same pitch) a wire coil that extended to the boiler tube exit. The instrumented centerbody extended to the exit but had a 20-cm gap at the start of the wire coil (designed to prevent liquid flow along the upstream centerbody from being carried over onto the downstream centerbody).

The second boiler (with venturi) was similar to the first, except that at the boiler tube inlet a conically convergent-divergent venturi nozzle with a throat diameter of 0.193 cm was installed, with a central plug starting in the nozzle diffuser. Wrapped around the plug and extending the full length of the boiler tube was a helical wire coil. An instrumented centerbody was installed for only the last one-third of the boiler tube. The lithium heating fluid outlet from the shell was approximately 7.6 cm downstream of the potassium venturi exit.

The performance of these two boilers is shown in the next three figures, taken by General Electric under Contract NAS3-9426 and published in references 15 and 41. Typical temperature patterns throughout the length of the boiler without venturi are shown in figure 11, taken from reference 41. Similar

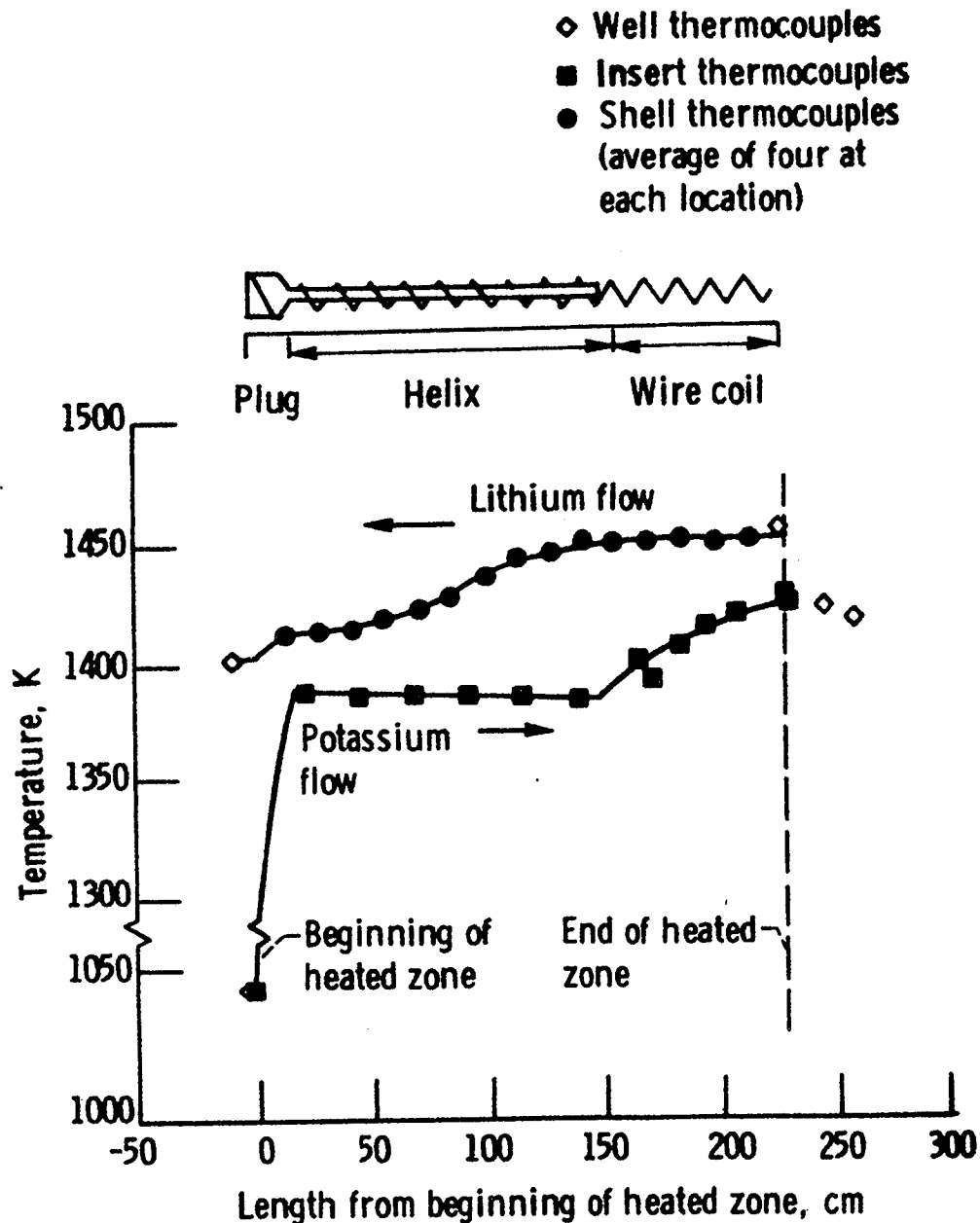


Figure 11.—Temperature distribution for boiler 1 (ref. 41). Heating-fluid flow rate, 0.42 kg/sec; boiling-fluid flow rate, 0.044 kg/sec; heating rate, 99.8 kW.

patterns for the boiler with venturi are shown in figure 12. Temperature distributions for the second boiler with flashing at the venturi are shown in figure 13. Except for the first few centimeters of the potassium flow, these temperatures are comparable to those of figure 12, without flashing. Very high heat transfer coefficients were obtained in all three cases. Data from one test run on the boiler with venturi yielded an exit vapor superheat of 250 K above the exit saturation temperature of 1090 K, believed to be the highest superheat achieved in any potassium boiler—at that time (ref. 15). The maximum thermal power attained was about 0.21 MW_t. Generally the pressure losses were nearly constant over a range of potassium flow rate at constant thermal power until vapor superheat was obtained, and the pressure loss increased substantially. Essentially, the second boiler had a higher pressure drop, directly attributable to the venturi ΔP . The boiler with venturi was more stable in operation and performed thermally at least as well as without.

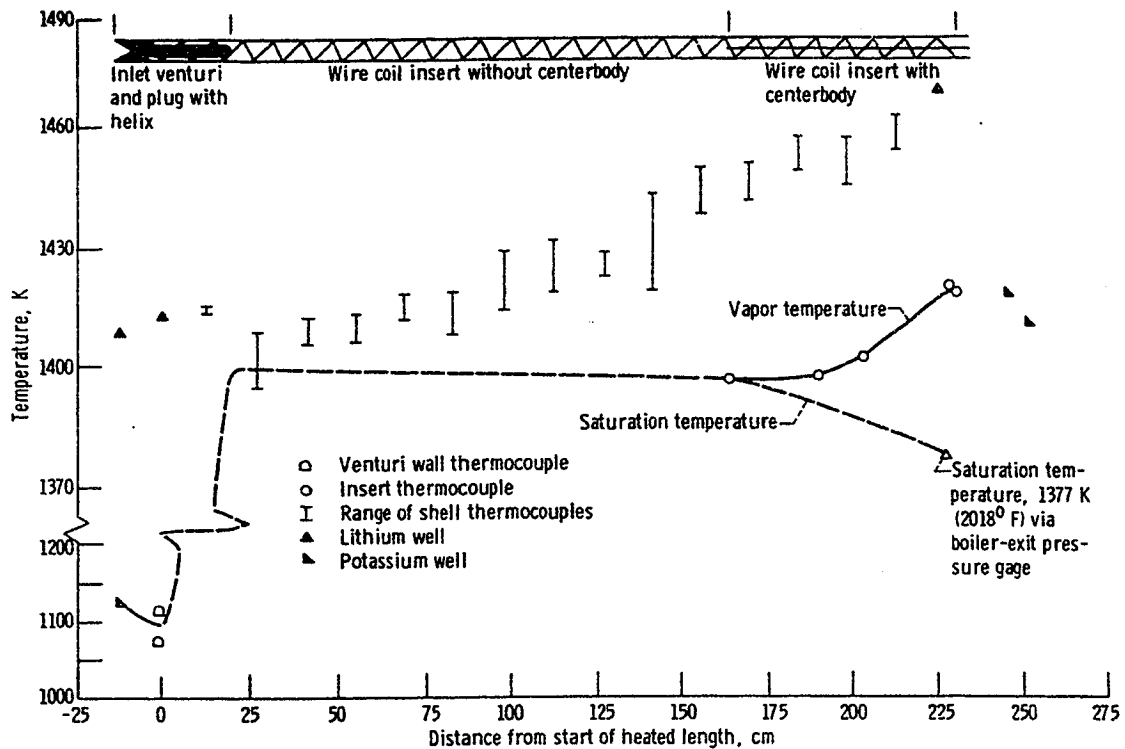


Figure 12.—Uncalibrated lithium and potassium temperature profiles through boiler 2 during design point demonstration runs. Heating-fluid flow rate, 0.409 kg/sec; boiling-fluid flow rate, 0.0500 kg/sec; heating rate, 94.6 kW; boiling-fluid pressure drop (venturi exit to boiler exit), 152 kN/m²; boiler-exit pressure, 1103 kN/m² abs; nozzle-inlet pressure, 1400 kN/m² abs; nozzle-inlet temperature, 1135 K; boiler-exit temperature minus boiler-exit saturation temperature, 44 K; nozzle-inlet temperature minus nozzle-exit temperature, 59 K; venturi liquid flooded.

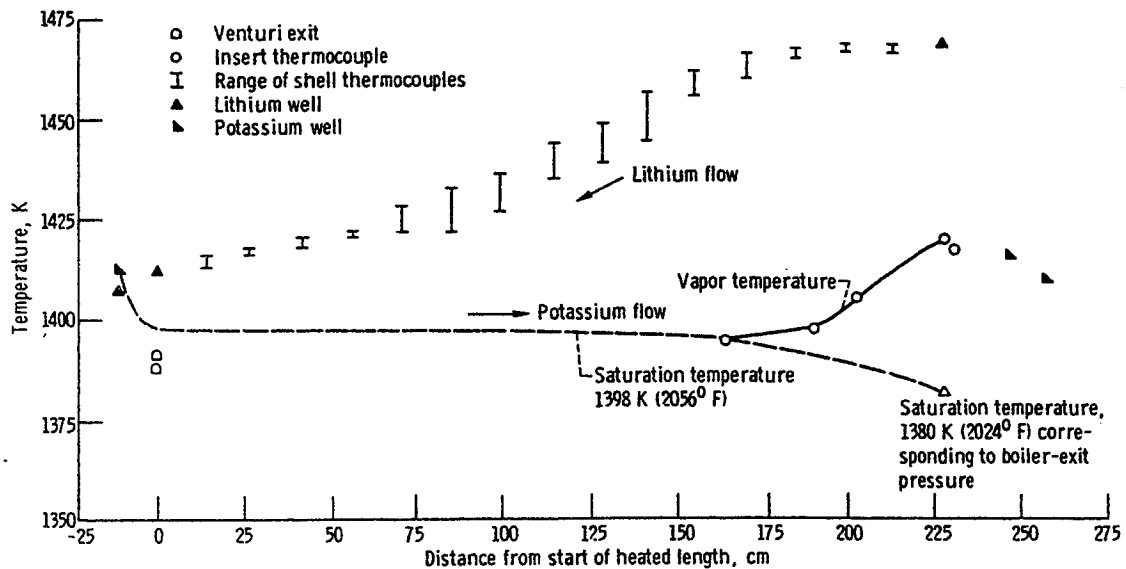


Figure 13.—Calibrated lithium and potassium temperature profile through boiler 2 with flashing at inlet venturi. Heating-fluid flow rate, 0.399 kg/sec; boiling-fluid flow rate, 0.0503 kg/sec; heating rate, 87.5 kW; boiler pressure drop 99 kN/m² boiler exit pressure, 1125 kN/m² abs; nozzle-inlet pressure, 1157 kN/m² abs; nozzle-inlet temperature, 1413 K; boiler-exit temperature minus boiler-exit saturation temperature, 40 K; heating fluid inlet temperature minus heating-fluid exit temperature, 57 K; flashing at venturi.

Rotating boiler.—A more novel approach to producing dry vapor stably is to rotate the boiler, as shown schematically in figure 14. Experiments on such a boiler are reported in references 43 and 44. A rotating boiler has many obvious advantages. It is insensitive to gravity field and orientation. The liquid-vapor interface is rather sharp and stable, yielding a steady flow of both vapor and liquid. Because of the centrifugal action on droplets in the vapor space the exit vapor should have low moisture content (high quality). The use of a rotating boiler, however, requires moving parts and rotating seals.

Some general comments about the rotating boiler operation are pertinent to understanding its performance. The boiler had an approximately constant volume inventory of fluid but with a continuous throughflow, the rate of which was determined by the heating rate. At low heating rates (and therefore low flows), the boiler liquid inventory was large relative to the throughflow, and pool boiling was approximated. Because of the annular symmetry of the boiler and the several small holes for the liquid inlet, the boiler liquid inventory rotated with the heated wall, in “wheel” flow. At high heating rates, throughflow was larger and, at high accelerations, vigorous secondary-flow cells developed in the boiler annulus as a result of convection.

The rotating boiler is a low-pressure drop device. This is an important consideration in a Rankine cycle system; however, this is partially offset by the power required to rotate the boiler. The liquid flow into the boiler and the vapor flow out were both steady. It was not necessary to add baffles or vanes to the boiler to correct for interface waviness or unbalance. The exit vapor quality was always well above 0.99. Exit vapor superheat was observed for five cases. The vapor outflow could not come in contact with the heated surface as in conventional boiler tubes near the exit. At very high accelerations, vapor apparently left the interface at several degrees above saturation temperature, probably as a result of the pressure rise within the boiling annulus.

Cyclone boiler.—The cyclone boiler concept (fig. 15) represents an attempt to combine the benefits of the rotating boiler with the simplicity of having no moving parts. The liquid or two-phase feed flows directly into the boiler tangentially in such a manner that a vortex flow pattern is established. The liquid is centrifuged to the wall and is then driven toward the apex of the cone by secondary flow effects (ref. 45) augmented by surface tension, while the vapor exits from the opposite end.

In order to study the two-phase flow in a cyclone boiler, in particular the effect of inlet geometry, air/water tests were conducted with transparent models (ref. 15). Two configurations were tested with conditions simulating the inlet conditions to a boiler, and good results were obtained. However, due to the termination of this program, no heated results were obtained at that time. In the mid-1980's, the concept

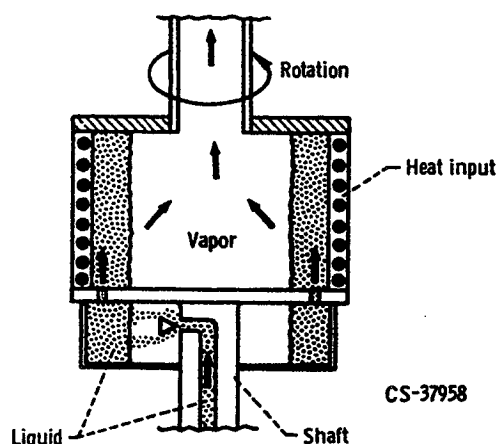


Figure 14.—Rotating boiler concept.

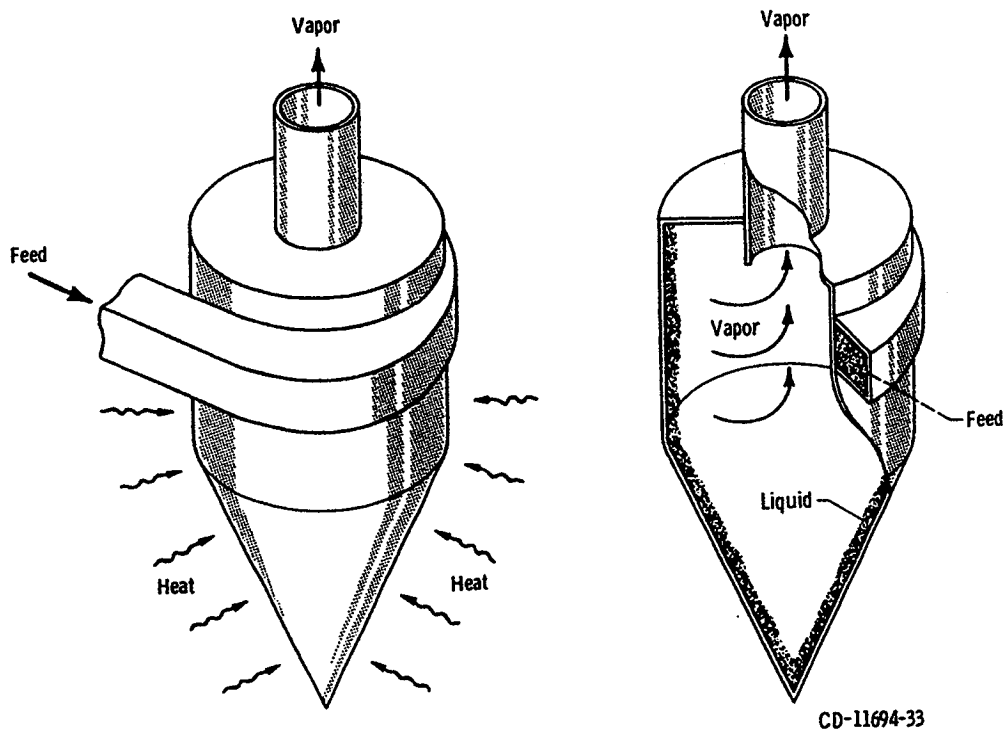


Figure 15.—Cyclone boiler concept.

became of interest as the vaporizer for a liquid-fed resistojet for low-thrust space propulsion, and tests were successfully conducted at very low power (ref. 46). Because of the very low powers and flow rates, insensitivity to gravity was not demonstrated, but superheated vapor was obtained in both horizontal and vertical orientations, but with much different heat transfer efficiency.

The cyclone boiler appears to be capable of providing moisture-free vapor at a steady rate. Distinct separation of liquid and vapor can be achieved without the use of inserts, thus making the cyclone boiler a relatively low pressure drop device.

CONCLUDING REMARKS

A substantial technology legacy exists for Rankine cycle systems from work done in the 1960's and 1970's, which can be utilized in reducing risks and costs of operational systems. Alkali metal boilers for Rankine cycle power conversion system applications were tested by NASA and industry. The major problems encountered were materials compatibility (not discussed in this report), stability, and droplet carryover from the boiler.

The flashing venturi inlet approach was developed and demonstrated near the end of this program which greatly alleviated the stability and carryover problems. The flashing venturi is a proven concept, giving good results with both water and potassium boilers when used in conjunction with flow-swirling inserts (the potassium boiler tube was also curved, further promoting secondary flows and relieving mechanical stresses. This approach merits serious consideration for future development, since not only does it offer stable, high-efficiency performance, but its use may help provide economies in the development program. The development benefits derive from the fact that by fixing the point of initiation of vaporization, water becomes an excellent simulator of potassium; subcooled boiling (with water) and superheated liquid (with potassium) are avoided. Therefore, design options and multiple-tube configurations can be tested in water, with final verification in potassium.

Further legacy from the earlier work can be found in two promising advanced concepts, the rotating boiler and the cyclone boiler. The rotating boiler has been very successfully demonstrated with water. The cyclone boiler is very promising, but is unproven except at very low power.

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13. ABSTRACT (Maximum 200 words) Alkali metal boilers are of interest for application to future space Rankine cycle power conversion systems. Significant progress on such boilers was accomplished in the 1960's and early 1970's, but development was not continued to operational systems since NASA's plans for future space missions were drastically curtailed in the early 1970's. In particular, piloted Mars missions were indefinitely deferred. With the announcement of the Space Exploration Initiative (SEI) in July 1989 by President Bush, interest was rekindled in challenging space missions and, consequently in space nuclear power and propulsion. Nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) were proposed for interplanetary space vehicles, particularly for Mars missions. The potassium Rankine power conversion cycle became of interest to provide electric power for NEP vehicles and for "dual-mode" NTP vehicles, where the same reactor could be used directly for propulsion and (with an additional coolant loop) for power. Although the boiler is not a major contributor to system mass, it is of critical importance because of its interaction with the rest of the power conversion system; it can cause problems for other components such as excess liquid droplets entering the turbine, thereby reducing its life, or more critically, it can drive instabilities—some severe enough to cause system failure. Funding for the SEI and its associated technology program from 1990 to 1993 was not sufficient to support significant new work on Rankine cycle boilers for space applications. In Fiscal Year 1994, funding for these challenging missions and technologies has again been curtailed, and planning for the future is very uncertain. The purpose of this paper is to review the technologies developed in the 1960's and 1970's in the light of the recent SEI applications. In this way, future Rankine cycle boiler programs may be conducted most efficiently. This report is aimed at evaluating alkali metal boiler technology for space Rankine cycle systems. Research is summarized on the problems of flow stability, liquid carryover, pressure drop and heat transfer, and on potential solutions developed, primarily those developed by the NASA Lewis Research Center in the 1960's and early 1970's.				
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